Hydrodynamics modeling of the dynamics of Sn droplet target for the EUV source

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Contents

- Introduction and motivation
- Modeling of hydrodynamics and method of calculation
- Result of test calculation
- Summary

Scenario of excitation of LPP EUV source

prepulse

1μs

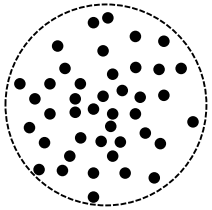
mainpulse

10ns

20μmϕ

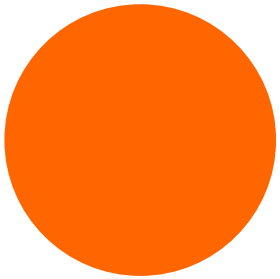
droplet

200μmϕ



mist

uniform plasma



EUV emission

radius	density
20μm	$3.5 \times 10^{22}/cm^3$
200μm	3.5×10^{19}
2mm	3.5×10^{16}

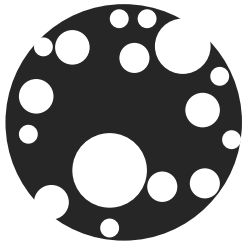
High CE is obtained with low density

Motivation of modeling Sn droplet dynamics

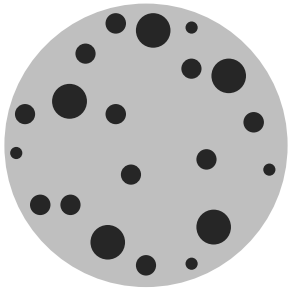
- High CE is obtained using prepusle technique; heating Sn mist produced by prepulse irradiation.
- Optimization based on hydrodynamics simulation is useful for further improvement of CE and power, development of BEUV sources.

  - Spatial temporal evolution of mist, distribution of particles.
  - Absorption of main laser pulse by particles.

Mechanism of formation of mist

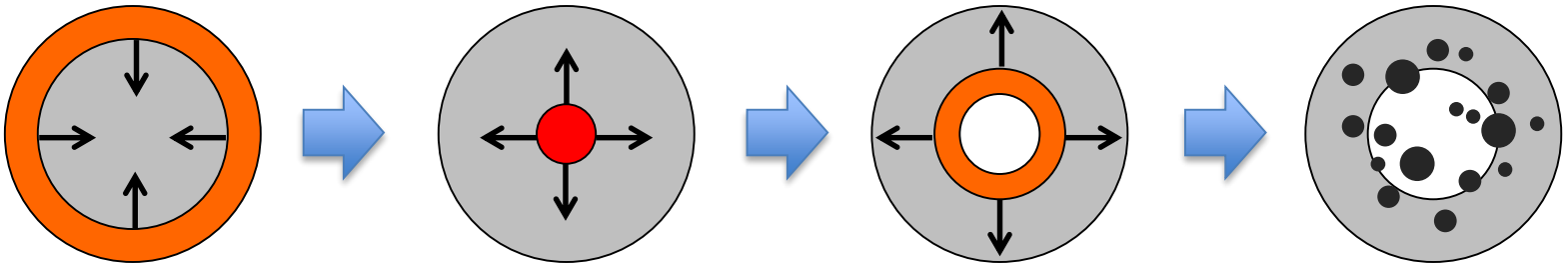


Boiling and evaporation of hot liquid



Condensation in adiabatic expansion of gas

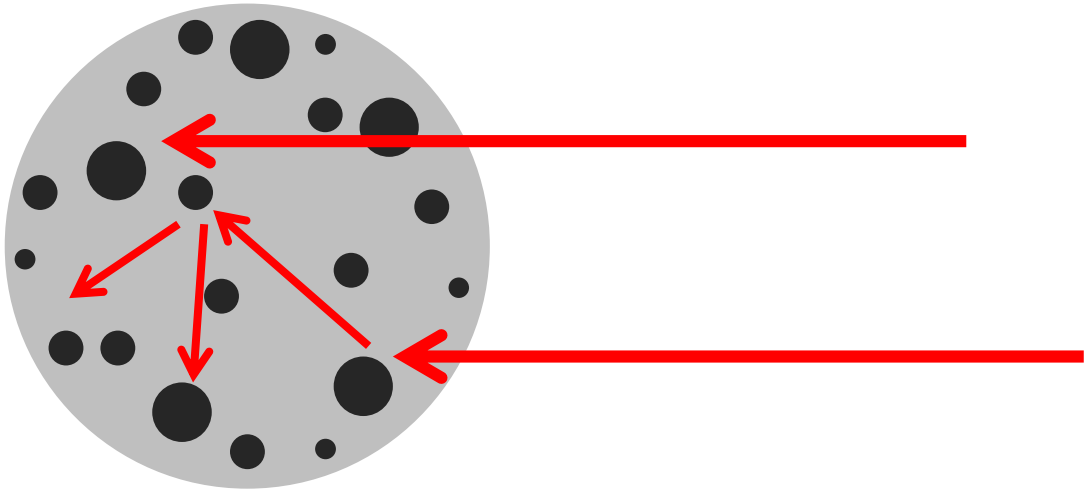
Hydrodynamics simulation of prepulse interaction



Inward shock wave is driven by short pulse laser irradiation

Outward fluid motion and fragmentation are driven by expanding shock wave

Interaction between mist and laser



- Laser penetrates into mist to produce uniform plasma with a large volume.
- Energy of laser is absorbed efficiently after multiple scattering.

2D Self-organizing Lagrangian hydrodynamics code

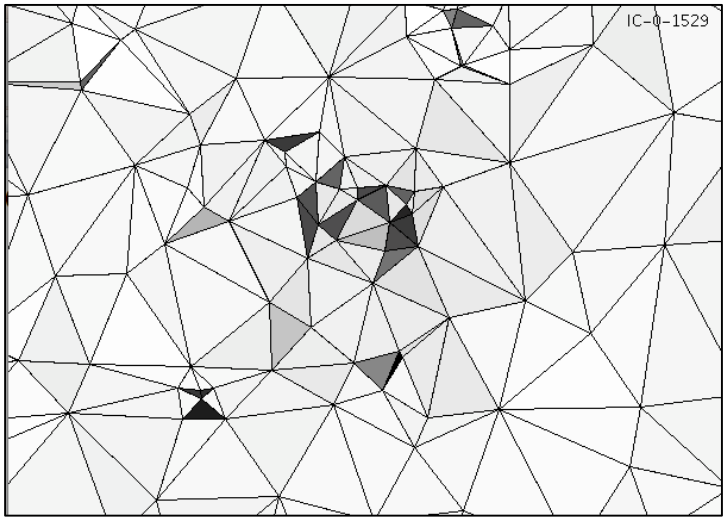
- Basic equations

equation of motion	$\frac{1}{r}\frac{d\mathbf{u}}{dt} = -\nabla P$
energy equation	$C_V \frac{dT}{dt} + B_T \frac{dr}{dt} + P\frac{dV}{dt} = S$
equation of state	

- Physics of laser produced plasma (heat conduction, ionization, radiative transfer) is included in the source term of the energy equation.
- Liquid-gas phase transition is included.

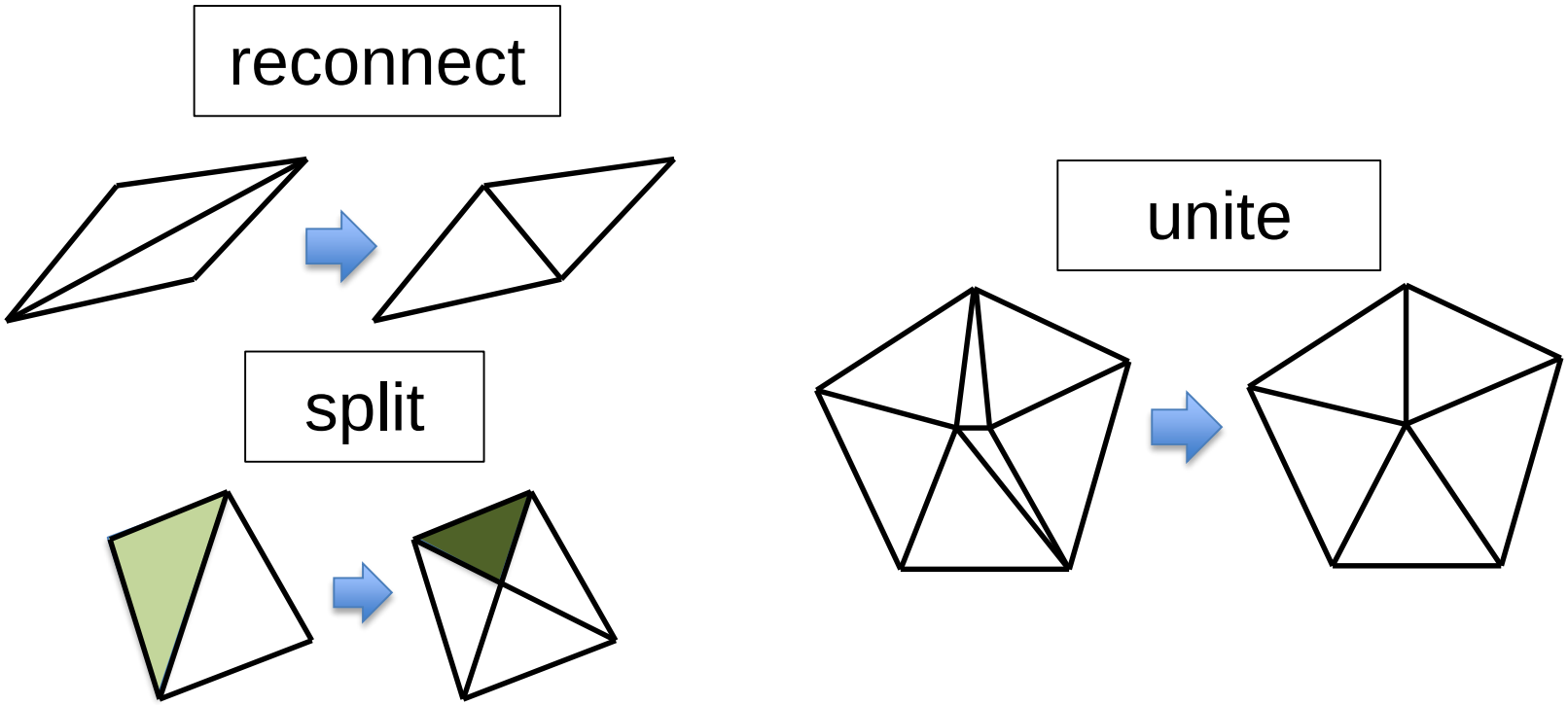
Triangular mesh

- Lagrangian grid which moves with fluid is useful for multi-physics simulation, however, application is limited by collapse of the mesh due to motion of the fluid.
- Triangular mesh is used for which an algorithm to avoid mesh collapse is developed and applied.



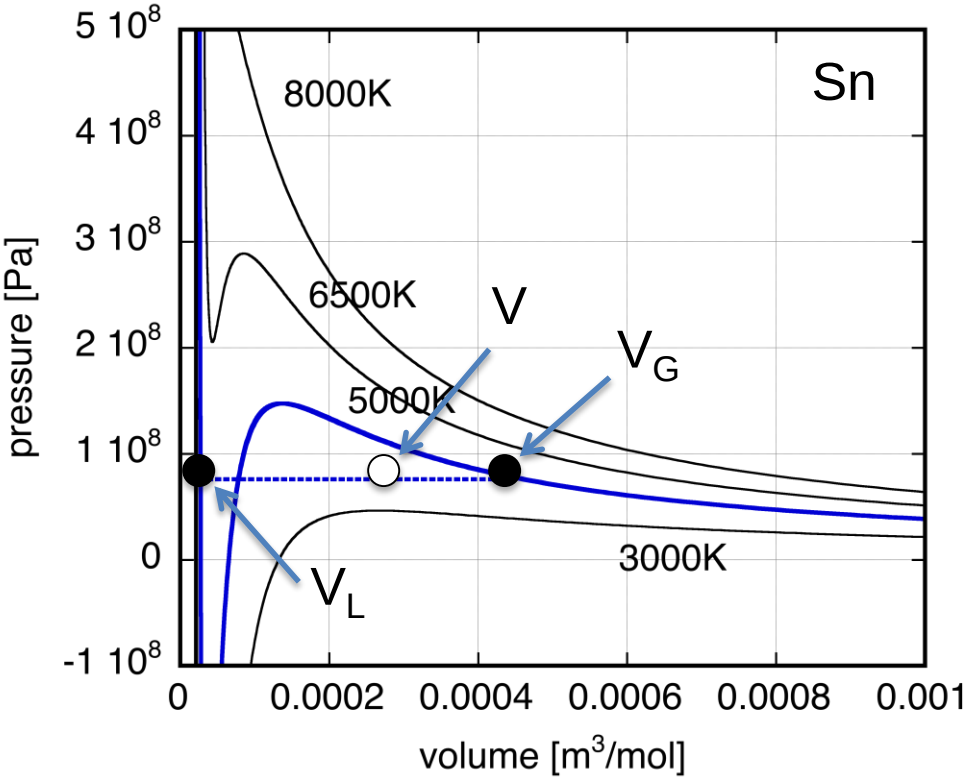
Reconnect, split, unite operations

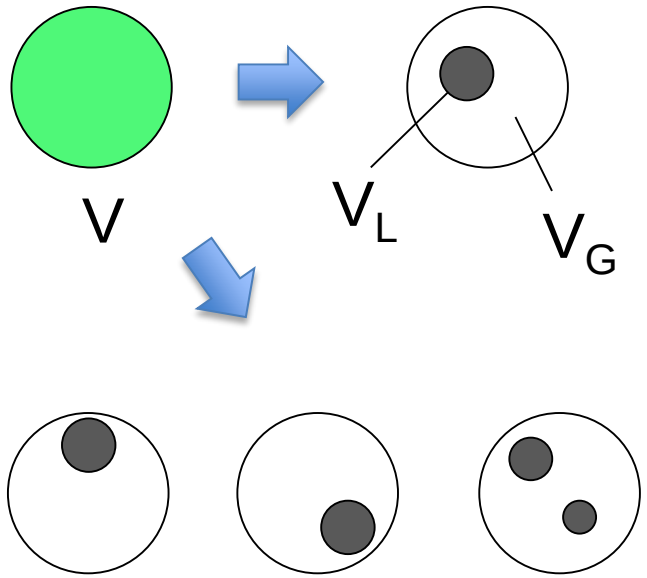
- Applying reconnect, split, unite operations to distorted cells, the mesh self-organizes to the fluid motion.
- The algorithm also allows the mesh to represent liquid clusters and gas bubbles in the fluid.



Model of liquid-gas phase transition

- Liquid-gas two phase condition is identified in phase diagram for thermal equilibrium.
- Two phase state is represented by splitting one cell to liquid and gas cell.



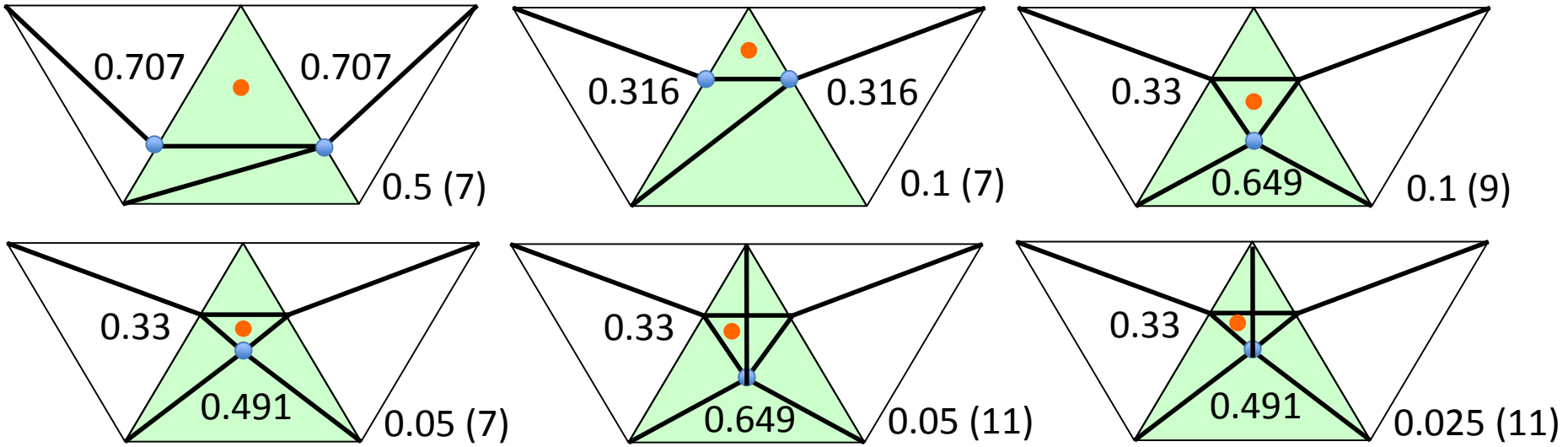


Equation of state for calculation of phase transition

- For gas phase, ideal gas law is applied.
- For liquid phase, pressure is assumed to depend only on temperature. The internal energy is determined by Dulong-Petit law (C_v=3kT), with offset to have the internal energy of both phase become equal at T_c.
- Transition point is determined by applying Maxwell's relation to Van-der-Waals equation of state of tin.
- At the transition, liquid-gas ratio is determined according to conservation of mass and volume; difference of the internal is released or absorbed as the latent heat.

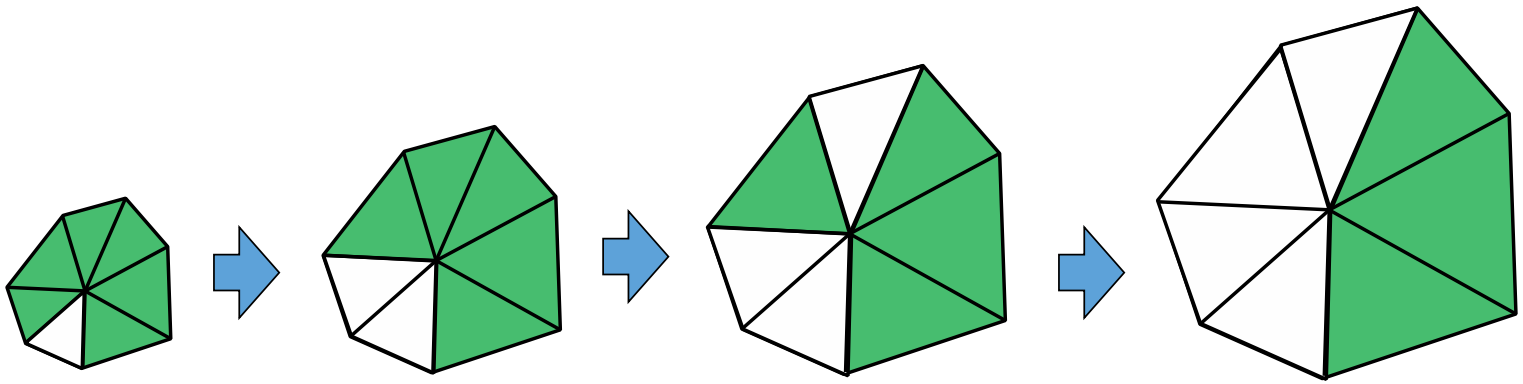
Model of liquid-gas phase transition

- Split a cell to 3 to 7 cells to represent correct liquid-gas phase ratio.
- Split cell operation is carried out including adjacent cells to maintain triangular mesh.
- Condition of nucleation is enforced numerically from possible liquid-gas ratio (2.5 – 97.5%).



Evaporation and condensation

- Bubbles and clusters will grow gradually during evaporation and condensation.
- Meta-cell is defined from a group of cells which share same point, and redistribute mass and internal energy to have correct liquid-gas ratio for the meta-cell.
- Number of liquid (gas) cells in a meta-cell is increased as the evaporation (condensation) proceeds.



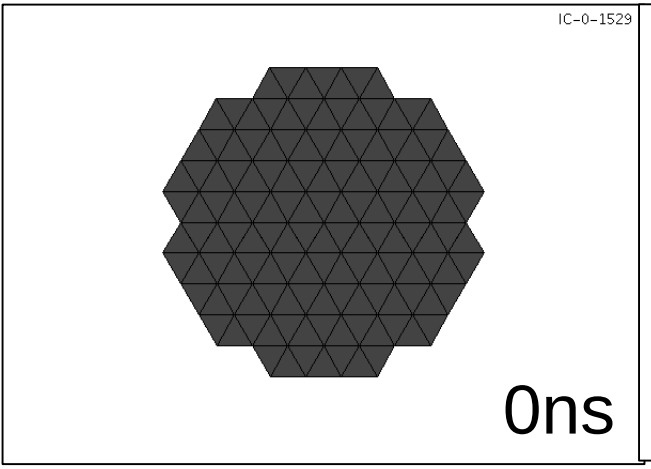
Test calculation

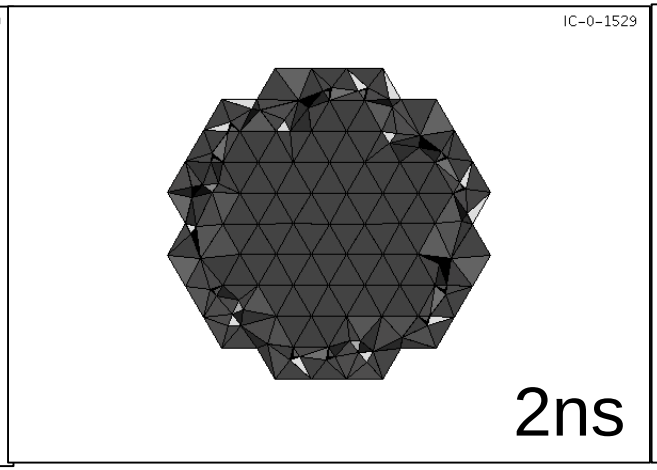
- Expansion of heated tin cylinder

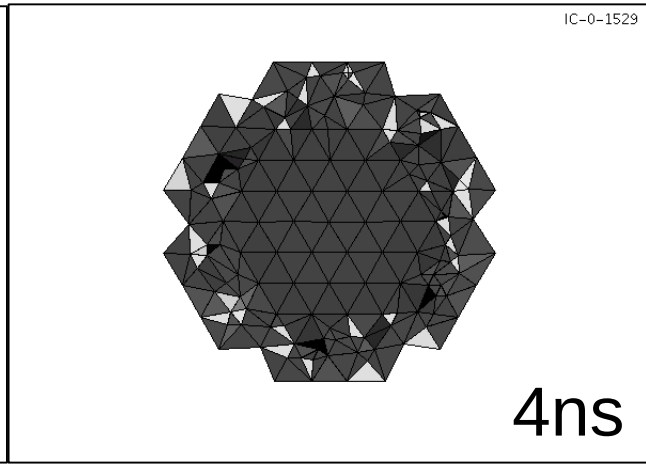
  radius = 10μm, density = 6000 kg/m^3

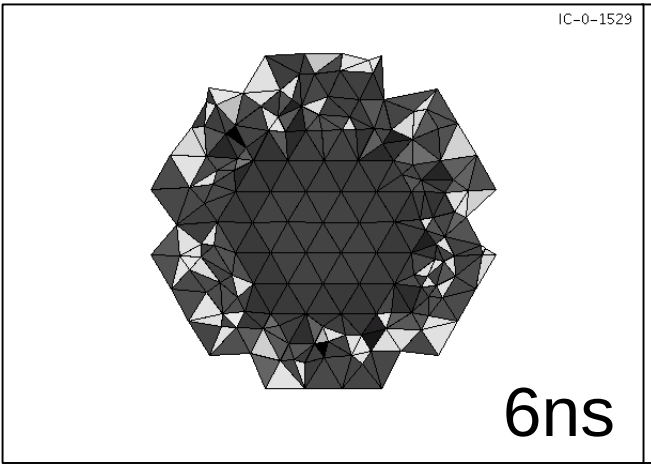
  temperature = 4000, 6000, 8000, 12000K

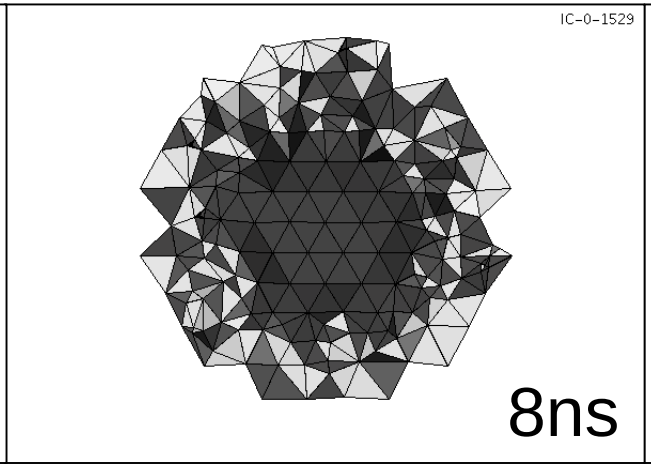
Evaporation of liquid tin (T=6000K)

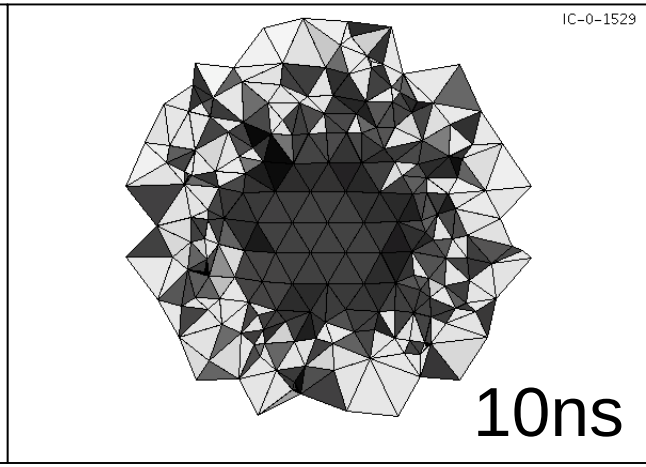




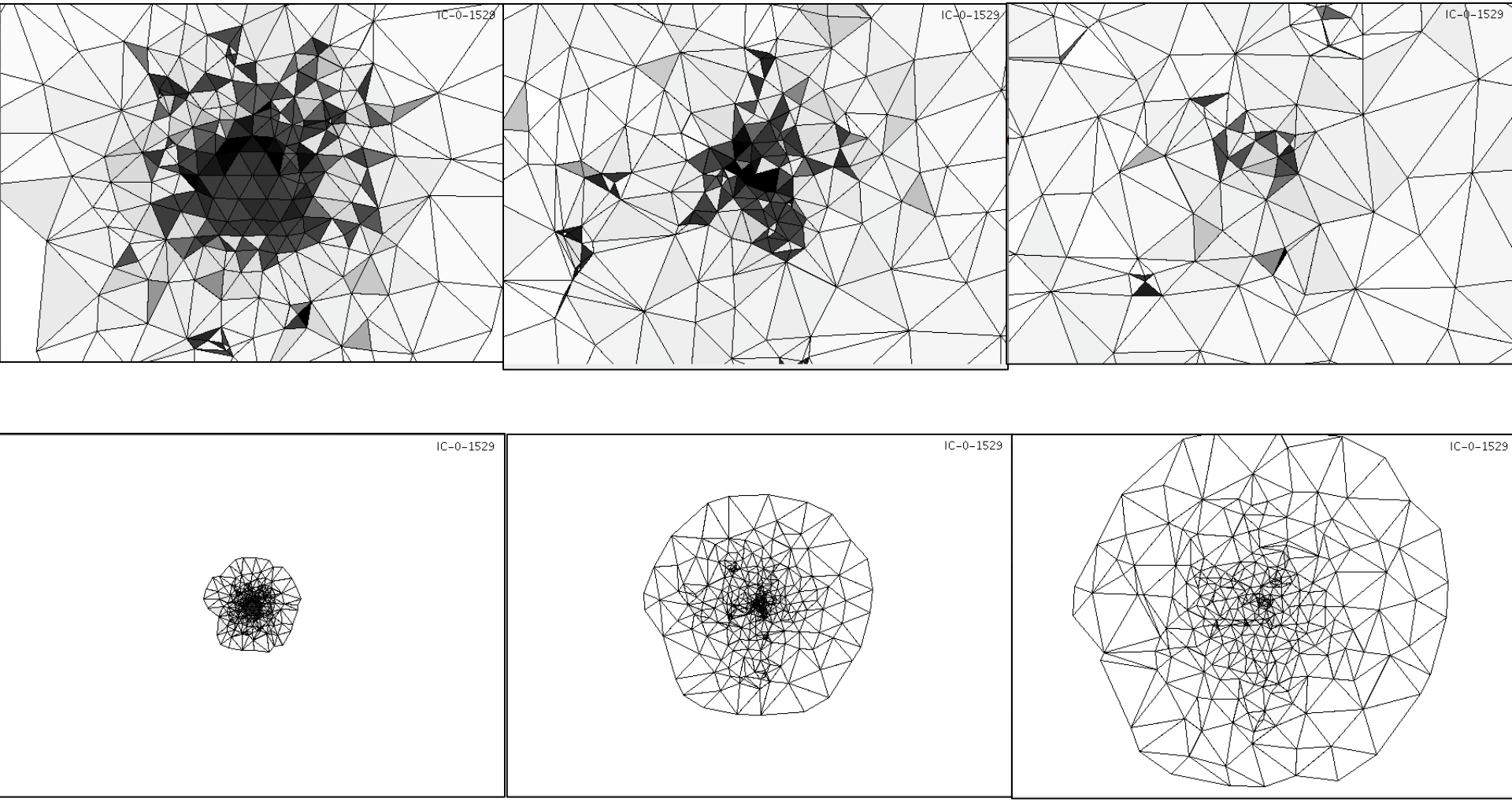








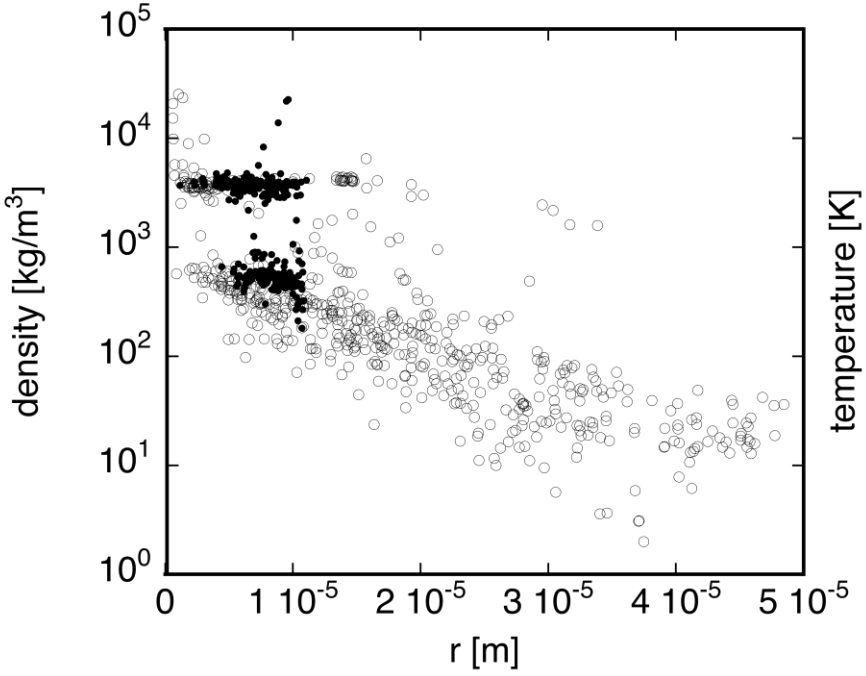
Evaporation of liquid tin (T=6000K) (late times)

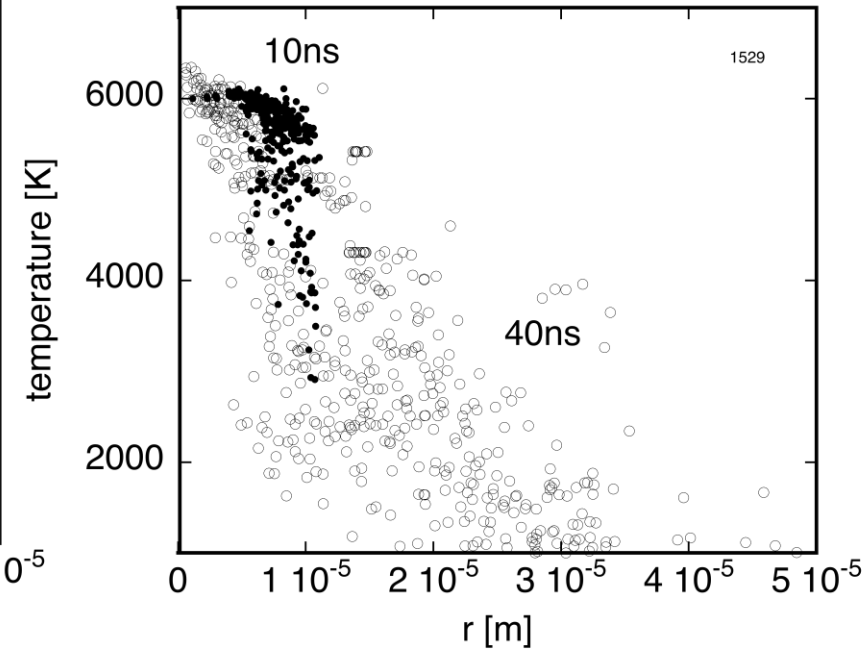


20ns 40ns 60ns

Evaporation of liquid tin (T=6000K)

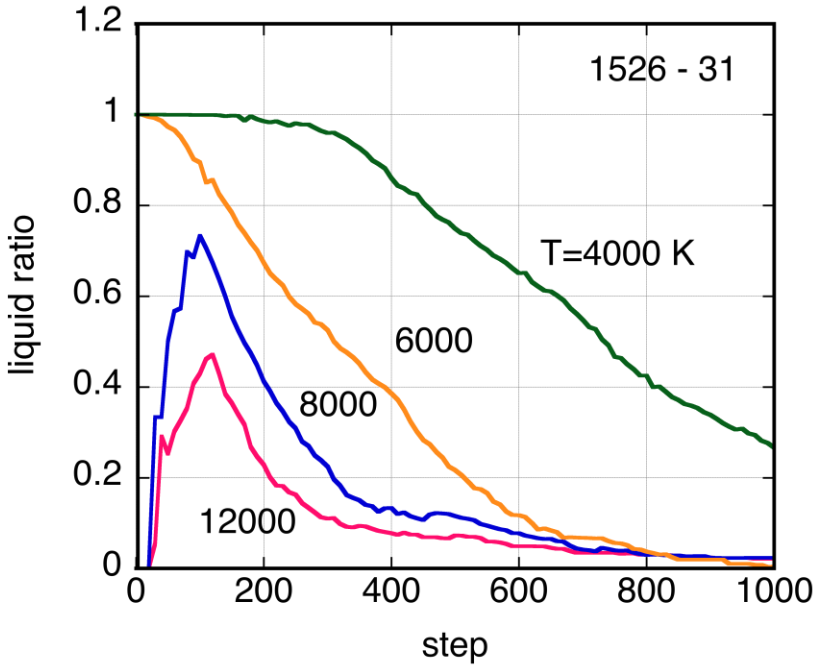
- Self organizing mesh including phase transition works as designed (almost).
- Heated liquid evaporates from surface leaving central core. Density gradient is caused by continuous supply of mass from core.

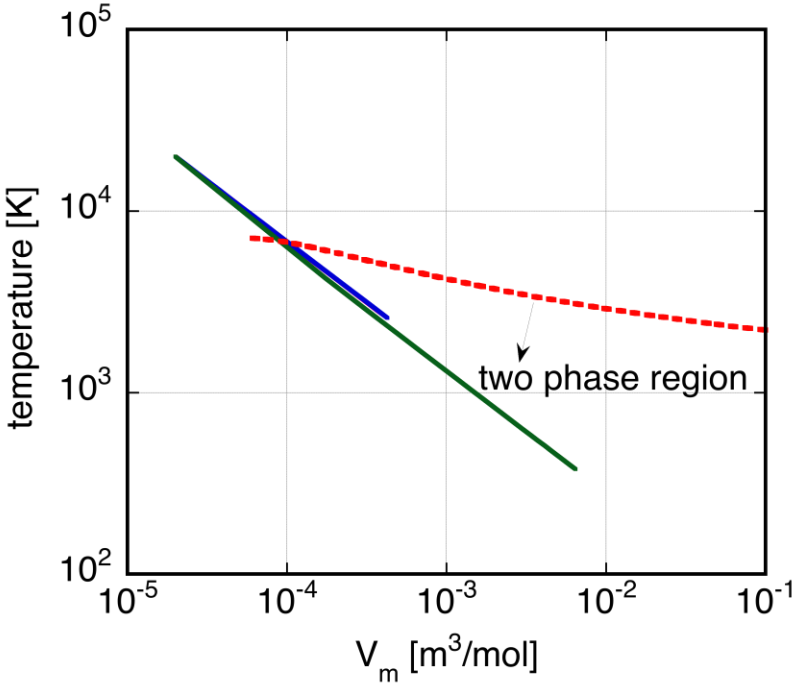




Condensation during expansion

- Hot liquid evaporates by expansion.
- Condensation occurs during expansion of hot gas in the two phase region to form clusters which eventually evaporates.





Heating mechanism of tin droplet

Heat capacity of tin : 27.1 J/mol K

Mass of droplet with r=10μm : 2.94 x 10^{-11} kg

Energy to heat up to 10000 K : 60μJ

Time for heat conduction $\Delta t = \frac{\rho R^2}{2k} C_v$ ≈ 100ns

Conductivity : 67 W/mK

- Energy required to heat droplet may be comparable to energy of prepulse laser absorbed, but heat conduction takes much longer time.
- Mist formation should rather be caused by shock wave driven by short prepulse as simulation suggests.

Summary

- Hydrodynamics code based on 2D self-organizing Lagrangian mesh is developed.
- Modeling methods to simulate mist formation by irradiating droplet by prepulse are investigated.
- Test calculations for expansion of heated tin are carried out, which shows evaporation of liquid tin and cluster formation of tin vapor during expansion.

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Near term plan

- Inclusion of physics of liquid to plasma state of tin will be completed, which allows the code to calculate shock wave driven mist formation by prepulse irradiation.
  - surface tension
  - heat conduction
  - laser absorption, ionization, radiative transfer

- Dependency on model parameters will be investigated to validate the simulation.